

A Modified Extensigraph Method for Evaluating Dough Properties of Hard Wheat Breeding Lines

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ABSTRACT

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A modified extensigraph method reduced sample quantity to 100 g from 300 g and testing time by half with easy dough preparation compared to the AACC standard extensigraph method, which challenges wheat breeding programs where the sample size is small and evaluations of large numbers of samples are demanded. Correlation coefficients (r) for 93 pairs of each of six extensigraph dough characteristics of 31 different tested wheat samples were $r = 0.95$ for resistance-to-extension, $r = 0.80$ for extensibility, $r = 0.93$ for ratio of resistance-to-extension to extensibility, $r = 0.92$ for ratio of maximum resistance-to-extension to ex-

tensibility, and $r = 0.81$ for area under the curve (energy). Correlation coefficients for the measurements of extensigraph dough characteristics at each of three rest-time tests between the modified and standard methods were significant. Some dough mixing characteristics and bake tests correlated better with dough extension characteristics when determined by the modified method. Repeatability of the modified method test was good. The modified extensigraph method can be a useful alternative to the standard method for the milling and baking industries, crop quality surveys, and wheat quality research.

Rheological characteristics of wheat flour dough with explicit, nonlinear shear thinning (pseudoplastic), and thixotropic behaviors (Weipert 1990) are complex and very important parameters for wheat quality evaluation and determination of end product quality. The complex and important rheological parameters, stress vs. strain, resistance-to-extension vs. extensibility, elasticity vs. viscosity, and maximum pressure vs. time taken for bubble to burst, can be measured with fundamental or empirical techniques. Fundamental measurements are not suited for establishing the possible relationship between the rheological properties of wheat flour dough and its baking behavior because the small deformations involved are completely different from the large deformations during fermentation and baking (Kokelaar et al 1996). However, rheological tests developed using either small or large strain levels give information that can be related to the structural characteristics of dough (Davidou et al 2008). The empirical tests have proven to be useful in practical industrial applications and continue to be used in research on wheat flour dough (Janssen et al 1996) because they generally correlate well with breadmaking performance (Tronsmo et al 2003).

The Brabender extensigraph is one of several empirical rheological instruments that offer a measurement of stress-strain relationship in dough after defined rest periods (Preston and Hoseney 1991). The extensigraph test can specifically determine dough extension characteristics that predict breadmaking quality or other end product qualities of wheat flour, estimate gluten quality, standardize optimum dough properties for baked goods, evaluate specific effects of dough ingredients and additives, differentiate qualities of breeding lines, improve the rapid screening of wheat cultivars, and control the flour quality for both the milling and baking industries (Bloksma 1990a,b; Hoseney 1994; Kokelaar et al 1996; Anderssen et al 2004; Mirsaeedghazi et al 2008). Although the standard extensigraph method has been widely used for many years, it requires a large sample size (300 g), which does not include amount of flour for determination of flour water ab-

sorption and mix time using the 50-g farinograph and a lengthy testing time with complicated dough preparation. Other instruments that are used for evaluation of dough extension characteristics include the Chopin alveograph and the TA-XT2i texture analyzer with a modified-geometry Kieffer rig used as a small-scale method (Kieffer et al 1998; Mann et al 2005). The alveograph method also requires a large sample size (250 g) and relies on identical water absorption and mix time for dough preparation. Large sample size and time requirements for both standard extensigraph and alveograph tests have precluded their general use for breeding programs in the United States (Nash et al 2006). Although a small flour sample was used for the TA-XT2i texture analyzer with a Kieffer rig, the data did not correlate with the standard extensigraph method, making the data interpretation difficult. In addition, very little information was reported about the reproducibility of the small-scale extension test (Dunnewind et al 2004). Thus, the standard extensigraph test has more advantages and benefits than other extension tests, but with some significant limitations such as requiring large amounts of flour, long testing times, and inconvenient dough preparation. Such limitations do not allow the standard extensigraph test to be used for evaluation of wheat samples in wheat breeding programs where sample size is small and evaluation is demanded of large number of samples. U.S. hard winter wheat breeders are interested in the dough extension tests for their breeding programs if the test requires small sample size (personal conversations). The USDA-ARS Hard Winter Wheat Quality Lab in Manhattan, KS, has conducted the standard extensigraph or alveograph tests on composite hard winter wheat breeding lines for some of hard winter wheat breeding programs in the Great Plains. Composite breeding lines were used for the dough extension tests because of lack of seeds in one location. Therefore, developing or modifying a method that requires a small amount of flour, cuts testing time, allows easy dough preparation, generates satisfying results, and has good repeatability for the dough extension tests on the extensigraph instrument could help avoid many limitations of the standard extensigraph and other tests and bring about a more efficient and effective evaluation of dough extension characteristics. Our objective was to modify the standard extensigraph method and minimize its limitations by reducing sample size and decreasing dough preparation time. A modified method that offered convenient dough preparation and required small sample size and less testing time would be available to evaluate flour samples in wheat breeding programs and available as an alternative to the standard extensigraph method for the milling and baking industries, wheat crop quality surveys, and wheat quality research.

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MATERIALS AND METHODS

Wheat Samples

Thirty-one hard winter wheat cultivars and advanced breeding lines (2006 and 2007 crop years) grown in seven states (Texas, Oklahoma, Kansas, Colorado, Nebraska, South Dakota, and Montana) were used in this experiment (Table I). These samples had been submitted for the Hard Winter Wheat milling and baking evaluation of the Wheat Quality Council located in Pierre, SD, where the mission is to advocate the development of new wheat cultivars that improve the value of wheat to all parties in the U.S. supply chain. The test weight of the samples was 74.9–84.1 (kg/hL) and the thousand kernel weight (TKW) was 22.3–37.9 (g). The wheat physical characteristics were evaluated using the Single Kernel Characterization System (Approved Method 55-31, AACC International 2000). Average wheat kernel hardness was 51–87, average kernel diameter was 1.87–2.65 (mm), and average kernel weight was 24.4–38.6 (mg). The wheat samples were milled with a Miag mill located in Kansas State University, Department of Grain Science and Industry. The straight-grade flour was used for all analyses, baking, and physical dough tests.

Flour Analysis

Untreated wheat flour samples were analyzed for moisture, ash, and protein content according to Approved Methods (44-15, 08-01, and 46-30, respectively) (AACC International 2000). Wheat flour protein content of the samples (14% moisture basis) was 10.6–14.0% (Table I). Flour ash content was 0.38–0.49%. Farinograph, mixograph, and extensigraph tests were conducted on the samples according to AACC Approved Methods (54-21, 54-40A, and 54-10, respectively). All samples were baked utilizing the pup loaf test according to AACC Approved Method 10-10B. Data of

bake mix time and loaf volumes generated by eight Wheat Quality Council collaborators was used to estimate the relationship with data generated by modified and standard extensigraph methods.

Modified Extensigraph Test

A 100-g micro mixer (National Mfg Division, TMCO, Lincoln, NE) was used for dough preparation with 100 g of flour (14% moisture basis) and a salt solution. The salt solution was prepared in a 100-mL plastic beaker using 2.0 g of salt (sodium chloride) and amount of distilled water (% as is) resulting in a 50-g farinograph consistency of 500 BU minus 2%, which was very close to the water absorption used for dough prepared in the 300-g farinograph in the standard extensigraph test. Dough mix time for the 100-g pin mixer was estimated using a 10-g mixograph. Flour dough was mixed to optimum development, which was determined by an experienced operator or baker. Optimum dough development occurs when the dough pulls away from the sides and bottom of the mix bowl and is smooth and clear in appearance. If the optimum point is passed, the dough will lose elasticity and become wet and sticky. Dough is usually smooth and clear appearance from the sides and bottom of the mix bowl after optimum development. The dough was then scaled to 150 g, rounded, molded, placed in an extensigraph dough holder, and rested for 30, 60, and 90 min in the extensigraph rest cabinets at 30°C. The dough was then tested as prescribed by the standard extensigraph method after each of three rest times. There was one piece of the dough per sample evaluated.

Statistical Analysis

All statistics were calculated using a statistical data analysis of Excel program for correlation coefficients.

TABLE I
Physical and Chemical Properties of Wheat Samples Grown at Different Locations in 2006 and 2007^a

Samples	State ^b	Test Wt (kg/hL)	TKW (g)	SKCS Results				
				Kernel Hardness	Kernel Size (mm)	Kernel Wt (mg)	Flour Protein (14% mb)	Flour Ash (14% mb)
Hatcher	CO	82.3	31.4	60	2.29	33.1	13.54	0.42
CO03W239	CO	80.9	30.1	64	2.22	30.5	13.23	0.39
CO03W054	CO	80.9	30.8	70	2.34	32.4	13.35	0.45
CO02W237	CO	81.5	28.4	53	2.11	29.5	13.25	0.40
Millennium	NE	77.5	26.4	66	2.13	29.2	11.91	0.48
NH03614	NE	77.5	28.8	55	2.32	32.4	11.03	0.44
OK Bullet	OK	83.5	31.7	77	2.55	33.5	12.40	0.46
OK00514	OK	82.9	31.3	80	2.55	33.6	11.61	0.48
OK05737W	OK	80.2	27.5	65	2.40	32.0	11.73	0.46
OK03522	OK	84.1	37.9	75	2.63	38.5	10.92	0.39
OK02405	OK	77.6	30.8	80	2.34	31.8	12.13	0.44
Tandem	SD	81.4	32.9	66	2.46	34.4	12.47	0.42
SD98W175	SD	81.4	27.8	70	2.22	29.2	12.30	0.44
SD01058	SD	80.1	30.6	57	2.16	31.4	11.94	0.41
SD0111	SD	80.9	32.6	68	2.41	33.9	12.39	0.48
SD01273	SD	80.9	32.8	72	2.27	33.1	11.12	0.46
Genou	MT	77.0	22.3	64	1.87	24.4	13.74	0.43
MT0495	MT	81.0	32.8	69	2.43	32.9	11.03	0.38
MTS04114	MT	82.0	33.2	56	2.41	35.5	11.72	0.39
Fuller	KS	79.1	37.5	51	2.65	38.6	13.25	0.38
KS990498	KS	76.1	32.1	65	2.34	33.9	12.11	0.41
KS970274	KS	80.2	35.0	67	2.64	35.8	12.34	0.39
Overley	KS	79.3	33.4	56	2.63	36.7	13.64	0.40
Smoky Hill	KS	79.7	30.0	62	2.41	33.0	12.83	0.49
Aspen	KS	79.2	36.4	62	2.57	38.0	13.47	0.47
Duster	OK	83.5	29.0	87	2.32	30.0	10.64	0.38
Tam 111	TX	79.1	28.9	62	2.20	29.8	12.18	0.41
Tam 112	TX	80.1	30.1	70	2.20	30.4	12.74	0.44
TX01A5936	TX	81.1	32.6	61	2.41	34.1	13.36	0.39
TX01D3232	TX	76.5	28.6	68	2.19	28.2	12.55	0.40
TX01V5314	TX	74.9	27.1	64	2.11	29.2	13.96	0.48

^a Test Wt, test weight; TKW, thousand kernel weight; Kernel Hardness, single kernel hardness; Kernel Size, single kernel size; Kernel Wt, single kernel weight.

^b CO, Colorado, NE, Nebraska, OK, Oklahoma, SD, South Dakota, MT, Montana, KS, Kansas, TX, Texas.

RESULTS AND DISCUSSION

Farinograph Results and Dough Preparations for Extensigraph Tests

Table II summarizes the results of 50-g farinograph tests and water absorption and mix time used for the modified method to prepare dough in the 100-g mixer. The optimum water absorption determined by the 50-g farinograph test for the 31 flour samples was 55.9–66.4% on a 14% moisture basis, with an average of 60.8%. Average farinograph dough development time was 11.0 min; CO03W054 and Duster samples had the longest and shortest times at 26.3 and 1.9 min, respectively. Other farinograph results such as mix stability, mix tolerance index, and dough breakdown varied among the samples. These samples not only differed in dough physical properties as indicated by farinograph measurements, but also in protein content (Table I), locations, and sample sources.

Water absorption and mix time used to prepare dough in the 100-g mixer for the modified extensigraph test were 56.2–68.1% and 2.5–6.9 min, respectively. The mix time for dough preparation using the 100-g mixer with rotating pins was much shorter than dough made from the standard method using the 300-g farinograph with Z-blades. Average mix time for the 31 dough samples prepared in the 100-g mixer was only 4.1 min, at 2.5–6.9 min, while the average mix time was \approx 11.0 min, at 1.9–26.3 min if the dough was prepared in the 300-g farinograph for the standard extensigraph method. The dough mix time was much shorter in the 100-g mixer than in the farinograph if the farinograph mix time was >20 min. For example, dough mix time for CO03W054 was only 6.0 min in the 100-g mixer but 26.3 min in the farino-

graph. The mixing action in a pin mixer is the superposition of a large number of stretches and folds of the dough around the pins (Anderssen et al 1997; Gras et al 2000). Mixing on a 100-g mixer can be viewed as a series of extension tests (Anderssen et al 1997; Bekes et al 2000; Gras et al 2000), whereas the farinograph mixes in a different manner, through a pack and squeeze action (Mann et al 2008). This may be a reason why the mix time in a pin mixer is shorter than in a farinograph with Z-blades. In addition to the advantage of short dough mixing time, dough preparation using the 100-g mixer was easier, more convenient, and faster than dough preparation using the 300-g farinograph based on instrument operation, cleaning of mixing parts, and handling of the mix bowl. Therefore, the improved dough preparation in the 100-g mixer is more efficient and effective for the modified extensigraph test, and more samples can be evaluated on a daily basis for breeding programs, wheat crop quality surveys, and wheat quality research.

Repeatability of the Modified Dough Preparation

Repeatability of any test method is critical. Six flour samples were chosen at random from the 31 samples for evaluation to determine the repeatability of the modified extensigraph test. Dough extension measurements determined by the modified extensigraph methods for each of the six flour samples were conducted for three replicates. Means (Avg), standard deviation (SD), and coefficients of variation (CV) were calculated for the three replicates. Two samples were used as examples for discussion because the other four samples had similar results (Table III). The modified extensigraph method at 30, 60, and 90 min was encouraging by the good results based on means, standard deviation, and

TABLE II
Farinograph Results and Mix Time for Dough Prepared in a 100-g Mixer^a

Samples	50-g Farinograph					100-g Mixer		
	Water Abs (as is %)	Water Abs (14%mb)	Development Time (min)	Mix Stability (min)	MTI	Breakdown (min)	Water Abs (as is %)	Dough Mix Time (min)
Hatcher	65.1	62.3	12.3	27.3	10	30.2	63.1	3.8
CO03W239	64.2	60.4	11.5	24.6	12	27.5	62.2	3.6
CO03W054	70.1	66.4	26.3	28.7	0	34.1	68.1	6.0
CO02W237	65.1	61.6	11.0	31.4	9	34.0	63.1	4.3
Millennium	62.0	58.5	5.2	10.7	30	9.4	60.0	3.0
NH03614	58.8	55.9	6.5	18.5	13	20.1	56.8	4.1
OK Bullet	65.5	62.4	6.0	11.9	31	10.2	63.5	3.0
OK00514	65.1	62.2	6.3	14.9	23	12.8	63.1	3.4
OK05737W	62.3	60.5	6.2	14.9	20	12.5	60.3	3.4
OK03522	65.5	63.8	6.1	19.1	21	12.6	63.5	4.3
OK02405	63.0	60.8	20.2	31.6	0	34.2	61.0	5.9
Tandem	63.7	61.5	8.5	23.2	10	25.1	61.7	3.6
SD98W175	63.7	60.8	6.2	13.5	21	14.2	61.7	2.5
SD01058	62.2	60.3	8.5	20.2	15	22.0	60.2	3.3
SD0111	63.2	60.6	9.0	17.7	18	19.6	61.2	3.0
SD01273	64.1	61.9	6.2	14.0	18	14.5	62.1	3.0
Genou	63.8	62.0	25.3	35.2	10	40.5	61.8	5.5
MT0495	61.9	60.6	7.2	13.3	27	12.7	59.9	3.0
MTS04114	60.5	59.3	10.0	19.1	11	21.6	58.5	4.0
Fuller	62.0	59.6	22.2	31.9	8	33.6	60.0	5.8
KS990498	58.2	56.4	23.8	36.0	9	37.8	56.2	6.9
KS970274	58.6	57.8	18.5	29.0	4	30.4	56.6	6.0
Overley	63.9	62.3	22.0	28.9	19	30.8	61.9	4.8
Smoky Hill	59.7	57.3	8.5	32.2	16	34.2	57.7	5.4
Aspen	66.6	64.3	7.5	18.4	18	17.3	64.6	3.3
Duster	64.8	62.4	1.9	4.2	63	2.7	62.8	4.8
Tam 111	60.4	58.3	6.3	13.9	28	11.6	58.4	2.6
Tam 112	63.9	61.0	6.7	26.5	10	27.9	61.9	3.5
TX01A5936	63.8	61.5	7.5	12.5	26	15.1	61.8	3.1
TX01D3232	62.8	60.2	9.2	16.0	19	17.4	60.8	4.3
TX01V5314	64.6	62.4	8.8	16.3	15	19.2	62.6	3.8
Avg	63.2	60.8	11.0	21.1	17	22.1	61.2	4.1
Max	70.1	66.4	26.3	36.0	63	40.5	68.1	6.9
Min	58.2	55.9	1.9	4.2	0	2.7	56.2	2.5

^a Abs, absorption; MTI, mix tolerance index; Avg, average; Max, maximum; Min, minimum.

coefficient of variation for each of the six dough extension measurement traits. All traits were observed to have low CV and small SD. Therefore, this modified extensigraph method test is repeatable.

Correlations Between Modified and Standard Extensigraph Methods

The dough extension characteristics evaluated by the extensigraph tests included resistance-to-extension (R), extensibility (E), maximum resistance-to-extension (R_{max}), ratio of resistance-to-extension to extensibility (R/E), ratio of the maximum resistance-to-extension to extensibility (R_{max}/E), and area under the curve (W), which is a proportion of energy used for stretching a cylindrically shaped dough piece until the dough piece breaks. The resistance-to-extension is also referred to as dough strength (Kieffer et al 1998; Mann et al 2005). However, Rosada (2004) refers to the dough strength as a balance between dough extensibility and dough elasticity. The curve height (resistance-to-extension) and area under the curve are taken as measures of flour strength (Hoseney 1994). The term dough strength is not used here for discussion to avoid the various definitions for flour and dough strength. Each piece of dough was stretched three times at 30, 60, and 90 min. Two pieces of dough for each flour sample were tested using the standard extensigraph method and averaged for data results. The averaged data was then used for correlation coefficient analysis with data from dough prepared in the 100-g mixer for the modified extensigraph method.

Significant relationships between modified and standard extensigraph parameters were observed despite the different dough preparations. Resistance-to-extension (R) and maximum resistance-to-extension (R_{max}) obtained by the modified method were highly correlated with the data generated by the standard extensigraph method. Correlation coefficients (r) of 93 pairs of R and R_{max} between the modified and standard extensigraph methods are $r = 0.95$ ($P < 0.0001$) (Fig. 1) and $r = 0.93$ ($P < 0.0001$) (Fig. 2), respectively. The resistance-to-extension from the dough extension test was important because of its high correlation with breadmaking performances such as water absorption, mix time, and loaf volume. A good breadmaking-performance dough usually exhibits a good balance between dough resistance-to-extension and extensibility, as well as a maximum ability, not only to minimize gas cell breakage, but also to expand gas cell rising. Although R has a good correlation with R_{max} , they are different from one other. Anderssen et al (2004) found that the R_{max} represents an excellent basis for discriminating between wheat cultivars on the basis of glutenin composition. The modified extensigraph method was in agreement with the standard method for the dough strength-related parameters (R and R_{max}).

Extensibility is one of three rheological characteristics of wheat flour dough (Kokelaar et al 1996). Two other characteristics are strain hardening and resistance-to-deformation. There was a good correlation coefficient ($r = 0.80$) ($P < 0.0001$) of the 93 pairs of extensibility values between the standard and modified methods (Fig. 3). Nonetheless, the extensibility correlation coefficient was

TABLE III
Repeatability of Modified Extensigraph Method Based on Standard Deviation and Coefficients of Variation^a

Time (min)	Result	Energy (cm ²)	Resistance (R) (BU)	Extensibility (E) (mm)	Maximum (R_{max}) (BU)	R/E Ratio	R_{max}/E Ratio
CO02W237							
30	T1	121	474	144	650	3.3	4.5
30	T2	126	501	142	700	3.5	4.9
30	T3	132	504	149	669	3.4	4.5
30	Avg	127	493	145	673	3.4	4.6
30	SD	5.2	16.5	3.3	25.2	0.1	0.2
30	CV	4.1	3.4	2.2	3.8	3.5	5.2
60	T1	163	891	125	1,000	7.1	8.0
60	T2	178	884	132	993	6.7	7.5
60	T3	173	848	130	996	6.5	7.7
60	Avg	171	874	129	996	6.8	7.7
60	SD	7.7	23.1	3.6	3.5	0.3	0.2
60	CV	4.5	2.6	2.8	0.4	4.6	3.2
90	T1	166	999	122	999	8.2	8.2
90	T2	148	995	110	998	9.1	9.1
90	T3	175	999	125	999	8.0	8.0
90	Avg	163	998	119	999	8.4	8.4
90	SD	13.6	2.3	8.2	0.6	0.6	0.6
90	CV	8.3	0.2	6.9	0.1	6.9	7.1
OK Bullet							
30	T1	89	325	155	411	2.1	2.7
30	T2	82	303	152	390	2.0	2.6
30	T3	93	338	152	441	2.2	2.9
30	Avg	88	322	153	414	2.1	2.7
30	SD	5.6	17.7	1.7	25.6	0.1	0.2
30	CV	6.4	5.5	1.1	6.2	5.5	6.5
60	T1	108	386	156	498	2.5	3.2
60	T2	93	364	147	471	2.5	3.2
60	T3	111	407	151	542	2.7	3.6
60	Avg	104	386	151	504	2.6	3.3
60	SD	9.5	21.5	5.0	35.8	0.1	0.2
60	CV	9.1	5.6	3.3	7.1	5.0	6.8
90	T1	102	373	154	489	2.4	3.2
90	T2	111	380	157	522	2.4	3.3
90	T3	113	424	151	551	2.8	3.6
90	Avg	109	392	154	521	2.6	3.4
90	SD	6.1	27.6	2.9	31.0	0.2	0.2
90	CV	5.6	7.0	1.9	6.0	8.5	7.0

^a T1, first test; T2, second test; T3, third test; R_{max} , maximum resistance to extension; Avg, average; SD, standard deviation; CV, coefficient of variation.

lower than R or R_{\max} , possibly because 1) more flour components affect extensibility than resistance-to-extension; 2) extensibility is more sensitive than resistance-to-extension; and 3) flour water absorption affects the dough extensibility more than dough resistance-to-extension. Grausgruber et al (2002) found that there was a very low correlation coefficient of extensibility between standard extensigraph method and small-scale extension test using the TA.XT2i texture analyzer equipped with the Kieffer dough and gluten extensibility rig. Mann et al (2005) compared a small-scale (modified Kieffer) extension test with the standard extensigraph method and discovered that the extensibility obtained by the two methods was less related than the other dough strength parameters. This modified method is much better than the other modified extension tests based on the correlation coefficient of extensibility with the standard extensigraph method.

The area under the curve, referred to as energy, is proportional to deformation work (W) and indicates flour strength. The area under the curve determined by the modified method was correlated with measurements of area under the curve by the standard extensigraph method (Fig. 4). The correlation coefficient was $r = 0.81$ ($P < 0.0001$). In another micro-extensigraph study, Grausgruber et al (2002) found significantly lower coefficients for the area under the curve. In this study, the energy generated by the modified method was more highly correlated with loaf volume and dough mix characteristics than was the energy measured with the standard extensigraph method. Therefore, the modified extensigraph method could be more useful than the standard extensigraph method for predicting baking performance because dough preparation for the modified method is very similar to that for the breadbaking test, while it would not be very similar for the stan-

dard extensigraph method. Dough preparation affects dough rheological characteristics.

Figures 5 and 6 show the relationships of ratio of resistance-to-extension to extensibility (R/E) and ratio of maximum resistance-to-extension to extensibility (R_{\max}/E) between the modified and standard methods. Gas bubble expansion, which shows bread loaf volume quality (Anderson et al 2004), can be characterized either by R or by R_{\max} and extensibility, the correlation coefficients of each were: R/E ($r = 0.92$, $P < 0.0001$) and R_{\max}/E ($r = 0.91$, $P < 0.0001$). A good balance between the two factors, resistance-to-extension and extensibility, is indicative of the dough expansion and gas holding capability. Janssen et al (1996) found that E/R_{\max} exhibited the same trend as did $\tan \delta$ (G'' [loss modulus]/ G' [storage modulus]), which can describe rheological properties of material. The best quality dough should have sufficiently high resistance to internal flow to prevent gas cells from coalescing and have sufficiently low resistance to internal flow to allow the gas cells to expand easily (referred to as extensibility). Therefore, the ratio value is one of the most important dough characteristics for bread dough quality.

Correlation coefficients of dough extension characteristics were assessed between the modified and standard extensigraph methods after each test of three dough rest times (30, 60, and 90 min) (Table IV). There was a significantly positive correlation in the dough resistance-to-extension at all the dough resting times, with values of $r = 0.91$ – 0.93 . Correlations between the two methods for R_{\max} were $r = 0.86$ at 30 min to $r = 0.95$ at 60 min. Correlations of the area under the curve (Energy) between two methods were $r = 0.83$ at 30 min, $r = 0.82$ at 60 min, and $r = 0.73$ at 90 min. The R_{\max}/E between the two methods had a high correlation, values of $r = 0.88$ – 0.91 . Correlation of E between the two methods increased with length of the rest time. Because flour dough

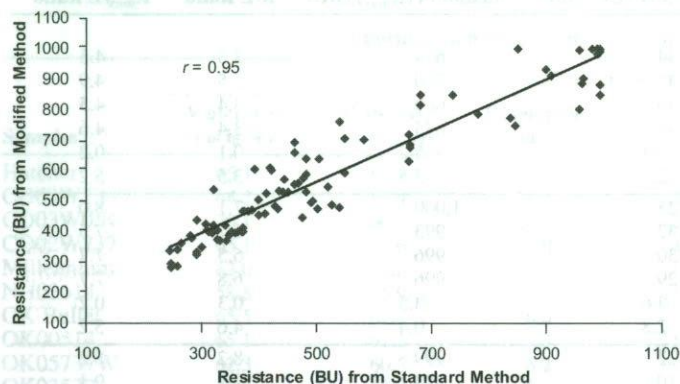


Fig. 1. Correlation of resistance to extension (R) between the modified and standard extensigraph methods ($n = 93$), significantly different at $P < 0.0001$.

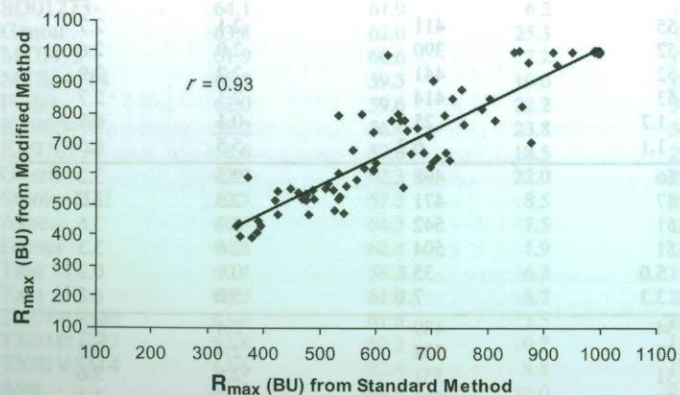


Fig. 2. Correlation of maximum resistance to extension (R_{\max}) between the modified and standard extensigraph methods ($n = 93$), significantly different at $P < 0.0001$.

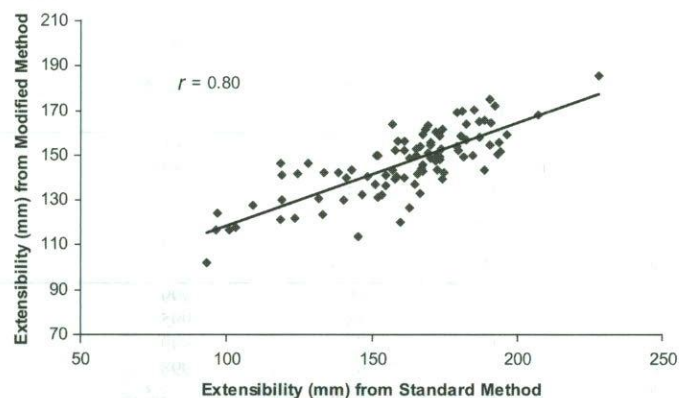


Fig. 3. Correlation of extensibility (E) between the modified and standard extensigraph methods ($n = 93$), significantly different at $P < 0.0001$.

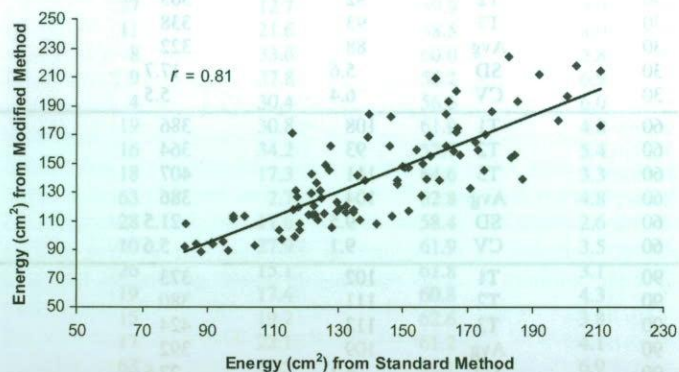


Fig. 4. Correlation of area under curve (W) between the modified and standard extensigraph methods ($n = 93$), significantly different at $P < 0.0001$.

exhibited time-dependent fluid behaviors, all tests of the three rest times (30, 60 and 90 min) of the modified and standard methods were required. Grausgruber et al (2002) found that this was unnecessary for the micro-method using the TA.XT2i texture analyzer equipped with the Kieffer dough and gluten extensibility rig.

Relationship Among Extensigraph Tests, Farinograph, and Bake Tests

Analysis was extended to examine the correlations of the extensigraph testing results with measurements of the farinograph and bake tests (Table V). Most of the farinograph traits were correlated with the dough extension measurements determined by the modified and standard extensigraph methods. Mann et al (2008) reported that the 50-g farinograph and 2-g mixograph mixing traits (except mixograph peak resistance) were not correlated with the extensibility determined by the standard extensigraph method. However, dough extensibility determined by the standard method at two tests (60 and 90 min) was significantly and negatively correlated with farinograph mixing traits. Correlation coefficients of the farinograph development time with extensibility at 60 and 90 min were $r = -0.89$ and -0.86 , respectively. Correlation coefficients between the dough extensibility evaluated using the modified method and farinograph mixing traits were low because the dough for the extension test was prepared in the 100-g mixer rather than in the 300-g farinograph.

The resistance (R) and R/E ratio of the dough extension characteristics measured by the modified method correlated higher with mix stability and MTI of farinograph dough mixing properties than with the standard method. Correlations of the farinograph mixing characteristics with some dough extension characteristics evaluated using the modified method were more constant at dif-

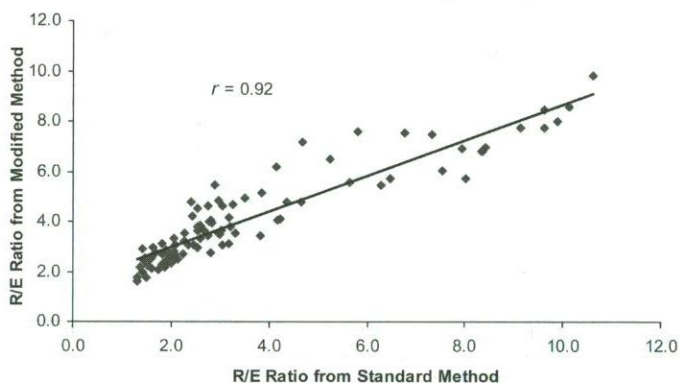


Fig. 5. Correlation of resistance to extension to extensibility (R/E) ratio between the modified and standard extensigraph methods ($n = 93$), significantly different at $P < 0.0001$.

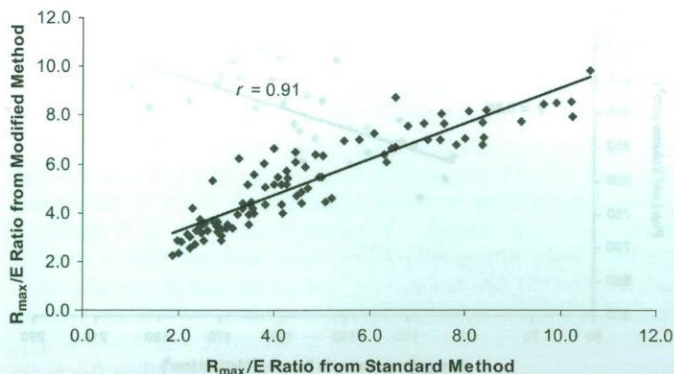


Fig. 6. Correlation of maximum resistance to extension to extensibility (R_{\max}/E) ratio between the modified and standard extensigraph methods ($n = 93$), significantly different at $P < 0.0001$.

ferent dough rest times than at the standard method (e.g., stability vs. energy, breakdown vs. energy, and MTI vs. energy). The differences in correlation coefficients of dough extension characteristics with the farinograph mixing properties resulted from two different mixing styles of dough preparation. The elastic portions of the deformations were approximately five times higher in the shear experiments than in the extension experiments. A small part of this difference could be explained by the longer recovery time (Bloskma et al 1988). Table V showed that correlations of area under the curve (energy) determined by the modified method with farinograph mixing traits were constant at tests of 30, 60, and 90 min. The constancy of the correlation indicated that the dough elastic recovery may be improved after the dough that was prepared in the 100-g mixer was stretched each time. The dough prepared in the 300-g farinograph may have been subject to extensive shearing, causing differences in recovery of the dough elasticity for different strengths of flour samples. Consequently, the correlation of farinograph mixing traits with energy measured by the standard method may be inconsistent. Therefore, the 100-g dough mixer may be more reliable and practical than the farinograph for extensigraph prepared tests.

The relationship between the bake test traits (bake mix time and loaf volume) and dough extension measurements determined by the modified and standard methods were examined. There were good correlations between bake mix time and dough extension characteristics (Table V). Correlations of the bake mix time with most of dough extension characteristics determined by the modified method were improved compared to the standard method. The mixing time required for optimum dough development was related to several stress-related dough properties. The correlation was positive with stress at a large strain and strain hardening and negative with the strain rate-dependency of the stress (Sliwinski et al 2004). The mix time required for different flour samples to achieve optimum dough development for either breadbaking tests, extension tests, or other tests was very important. A relatively good correlation coefficient was obtained for Energy (W) measured by the modified extensigraph method at dough extension tests of 60 and 90 min versus the loaf volume ($r = 0.73$). There was a weak correlation between loaf volume and extensibility determined by either the modified or standard methods in this experiment. In contrast, Zounis et al (1993) found that extensigraph length (extensibility) was correlated to loaf volume ($r = 0.61$). After W results at tests of 30, 60, and 90 min were

TABLE IV
Correlation Coefficients (r) of Dough Extension Characteristics Between Modified and Standard Extensigraph Methods^a

Time (min)	Dough Characteristics	Correlation Coefficients ^b (r)
30	Energy (cm ²)	0.83***
30	Resistance (BU)	0.91***
30	Extensibility (mm)	0.68***
30	Max Resistance (BU)	0.86***
30	R/E Ratio	0.88***
30	R_{\max}/E Ratio	0.88***
60	Energy (cm ²)	0.82***
60	Resistance (BU)	0.93***
60	Extensibility (mm)	0.70***
60	Max Resistance (BU)	0.95***
60	R/E Ratio	0.91***
60	R_{\max}/E Ratio	0.90***
90	Energy (cm ²)	0.73***
90	Resistance (BU)	0.93***
90	Extensibility (mm)	0.78***
90	Max Resistance (BU)	0.93***
90	R/E Ratio	0.91***
90	R_{\max}/E Ratio	0.88***

^a R/E, resistance to extension to extensibility; R_{\max}/E , maximum resistance to extension to extensibility; Max, maximum.

^b ***, Significantly different at $P < 0.0001$.

averaged, the average energy from either the modified or standard extensigraph methods was fairly well correlated with loaf volume (Figs. 7 and 8).

Relationship ($r = 0.72$) between the modified method and loaf volume was slightly better than between the standard method and loaf volume ($r = 0.68$). Nash et al (2006) found the area under the

curve to be a good predictor of final loaf volume and may provide a valuable measure to breeders in joint selection for optimal bread quality. Therefore, this modified extensigraph method seemed to be better than the standard method or at least a great alternative to it for wheat quality evaluation in terms of correlation of dough extension measurements with mixing and bake test traits.

TABLE V
Correlation Coefficients (r) of Farinograph Dough Properties and Baking Tests with Dough Characteristics of Modified and Standard Extensigraph Methods^a

Time (min)	Dough Extension Characteristics	50-g Farinograph Test				Bake Test	
		Develop Time (min)	Mix Stab (min)	MTI	Breakdown (min)	Bake Mix Time (min)	Avg Loaf Vol (cm ³)
Modified Method							
30	Energy (cm ²)	0.60**	0.67***	-0.57**	0.69***	0.78***	0.40*
30	Resistance (BU)	0.79***	0.81***	-0.77***	0.81***	0.84***	0.44*
30	Extensibility (mm)	-0.21 ^{ns}	-0.22 ^{ns}	0.31 ^{ns}	-0.16 ^{ns}	-0.07 ^{ns}	-0.06 ^{ns}
30	Max Resistance (BU)	0.73***	0.78***	-0.72***	0.79***	0.86***	0.43*
30	R/E Ratio	0.77***	0.78***	-0.78***	0.76***	0.77***	0.39*
30	R _{max} /E Ratio	0.78***	0.81***	-0.79***	0.81***	0.86***	0.42*
60	Energy (cm ²)	0.60**	0.65***	-0.68***	0.75***	0.81***	0.73***
60	Resistance (BU)	0.84***	0.81***	-0.79***	0.85***	0.91***	0.58***
60	Extensibility (mm)	-0.54*	-0.53*	0.59**	-0.53*	-0.14 ^{ns}	-0.11 ^{ns}
60	Max Resistance (BU)	0.71***	0.77***	-0.82***	0.85***	0.89***	0.63**
60	R/E Ratio	0.83***	0.78***	-0.78***	0.81***	0.84***	0.47*
60	R _{max} /E Ratio	0.75***	0.78***	-0.83***	0.83***	0.90***	0.51*
90	Energy (cm ²)	0.45*	0.61*	-0.65***	0.70***	0.67***	0.73***
90	Resistance (BU)	0.80***	0.83***	-0.79***	0.87***	0.84***	0.59**
90	Extensibility (mm)	-0.65***	-0.58**	0.58**	-0.58**	-0.52*	-0.20 ^{ns}
90	Max Resistance (BU)	0.64***	0.71***	-0.80***	0.81***	0.72***	0.66***
90	R/E Ratio	0.84***	0.80***	-0.76***	0.83***	0.81***	0.50*
90	R _{max} /E Ratio	0.75***	0.74***	-0.80***	0.80***	0.73***	0.53*
Standard Method							
30	Energy (cm ²)	0.74***	0.77***	-0.69***	0.82***	0.82***	0.46*
30	Resistance (BU)	0.93***	0.78***	-0.74***	0.81***	0.83***	0.43*
30	Extensibility (mm)	-0.51*	-0.26 ^{ns}	0.30 ^{ns}	-0.26 ^{ns}	-0.27 ^{ns}	-0.12 ^{ns}
30	Max Resistance (BU)	0.90***	0.80***	-0.74***	0.85***	0.87***	0.50*
30	R/E Ratio	0.91***	0.71***	-0.70***	0.74***	0.77***	0.38*
30	R _{max} /E Ratio	0.93***	0.76***	-0.73***	0.81***	0.84***	0.47*
60	Energy (cm ²)	0.34 ^{ns}	0.53*	-0.58**	0.61**	0.76***	0.58**
60	Resistance (BU)	0.93***	0.80***	-0.78***	0.84***	0.87***	0.59**
60	Extensibility (mm)	-0.89***	-0.68***	0.67***	-0.70***	-0.36 ^{ns}	-0.40*
60	Max Resistance (BU)	0.77***	0.76***	-0.81***	0.84***	0.85***	0.67***
60	R/E Ratio	0.96***	0.77***	-0.74***	0.80***	0.83***	0.53*
60	R _{max} /E Ratio	0.92***	0.79***	-0.81***	0.84***	0.85***	0.61**
90	Energy (cm ²)	0.01 ^{ns}	0.26 ^{ns}	-0.36 ^{ns}	0.36 ^{ns}	0.39 ^{ns}	0.49*
90	Resistance (BU)	0.87***	0.77***	-0.79***	0.83***	0.81***	0.62**
90	Extensibility (mm)	-0.86***	-0.68***	0.67***	-0.70***	-0.71***	-0.41*
90	Max Resistance (BU)	0.74***	0.76***	-0.82***	0.85***	0.68***	0.68***
90	R/E Ratio	0.93***	0.76***	-0.72***	0.80***	0.82***	0.55*
90	R _{max} /E Ratio	0.90***	0.78***	-0.78***	0.84***	0.78***	0.59**

^a MTI, mix tolerance index; *, **, ***, Significantly different at $P < 0.05$, $P < 0.001$, and $P < 0.0001$; ns, not significant.

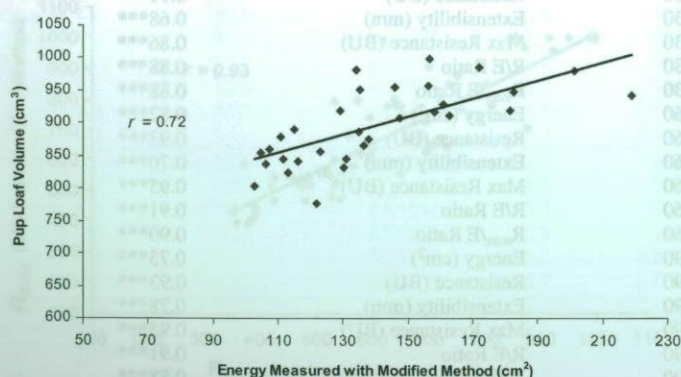


Fig. 7. Relationship between area under the curve (W) measured with the modified method and the pup loaf volume ($n = 31$), significantly different at $P < 0.0001$.

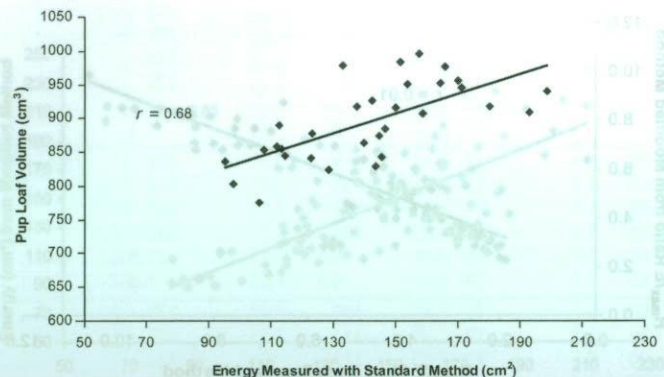


Fig. 8. Relationship between area under the curve (W) measured with the standard extensigraph method and the pup loaf volume ($n = 31$), significantly different at $P < 0.0001$.

CONCLUSIONS

Measurements of dough extension characteristics with this modified method are comparable to those generated by the standard extensigraph method. Therefore, this modified extensigraph method is a good alternative to the standard method and can be used to avoid limitations (sample size, testing time, throughput, dough preparation, and correlations of extension characteristics with dough mixing property and bake test) that the standard method has for wheat breeding programs.

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